AD P001949

PROBLEMS ASSOCIATED WITH THE AERODYNAMIC DESIGN OF MISSILE SHAPES

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Abstract

The purpose of the paper is to discuss various trends in the design of tactical missiles which influence the future directions of missile aerodynamics. Some of the subjects discussed include airframe-inlet interference, high angle of attack problems, waveriders, efficient hypersonic missiles, computational fluid dynamics applied to missile aerodynamics, aerothermal design and supersonic stores. A number of specific areas where increased emphasis is needed in missile aerodynamics are suggested.

1. Introduction

The purpose of this paper is the review of aerodynamic problems involved in the design of tactical missiles, both present and future. Many of the subsystems of missiles interact with the complete missile aerodynamic characteristics in ways which determine the important trends in the evolution of missile aerodynamics. One important subsystem is propulsion wherein the type of propulsion, airbreathing or non-airbreathing, is the significant parameter. The warhead size necessary to effect kill based on the CEP from the guidance and control sets the basic diameter of the missile. The guidance sensor characteristics such as frequency bandwidth, tolerable boresight error slope, and needed aperture influence the size and shape of the seeker dome. The launching platform usually imposes certain constraints on missile dimensions such as wing span. Nonlinearities in lateral-directional control and control cross-coupling interact strongly with the autopilot performance, or alternatively constrain the configuration or its responsiveness. Also, the structure and its vibration are strongly influenced by aerodynamics as a source of steady and unsteady loads as well as coupling between bending, vibration, and loads.

Some specific subjects of present and future interest are of particular importance in future missile designs. Since airbreathers are now receiving increased attention in the quest for battle space and for intercepting standoff targets, problems of interference between inlet and airframe arise. Hypersonic missiles are of great interest as a means of quickly neutralizing standoff targets, and achieving high L/D at high speeds through such devices as waveriders is receiving renewed emphasis. The carriage and delivery of stores at supersonic speed is of increased importance for penetration. High angle of attack aerodynamics has received much attention over the past several years, particularly as applied to enhance maneuverability of missiles, and many problems impacting aerodynamic design need more attention in this area. Improved accuracy of prediction methods for angles of attack greater than 20° is needed.

One discipline which can be brought to bear more heavily on missile design problems is computational fluid dynamics. It seems that missiles have not received the attention they deserve in this area, but there are signs of increased activity in this field. Applications of CFD to subregions of the missile flow field are frequently made at the present time, but applications to the complete missile flow fields are lagging.

There is a changing role of the missile aerodynamicist in missile design. In the past it has frequently been the practice to test the final design over the entire operating range in wind tunnels. It is now possible to do conceptual and trade-off studies up to angles of attack of about 20° using existing predictive methodology since more confidence is now placed in these methods than formerly. However, wind-tunnel tests for angle of attack above 20° are still required. As predictive methodology and CFD continues to improve, hopefully the amount of expensive wind-tunnel testing will be reduced although this can be argued. However, it is certain that missile aerodynamicists are making more extensive use of analytical tools.

In the following sections we will discuss in greater detail some of the subjects mentioned above. The treatment will necessarily be in breadth rather than depth.

A number of investigators have reviewed missile aerodynamics or special areas of it in References 1 to 7, and their work has been very helpful in preparing the present paper.

2. Problems in Airbreathing Missile Design

2.1 Introductory Remarks

Solid fuel rockets are the principal propulsion means of existing tactical missiles, and it is well known that the range of such missiles is limited by the fact that they must carry their own oxidizers. Increased missile range is needed to enlarge the battle space and to engage the enemy further out. It is also needed to counter stand-off jammers and to deny close-in airspace to reconnaissance aircraft. In addition there is a need to get out to the limits of the battle space quickly. These requirements lead to the future importance of the hypersonic air-breathing missile. Existing and developmental supersonic airbreathing missiles appear to operate with critical or supercritical flow in the inlet for simplicity. By-passing the extra airflow to avoid spillage or varying compression ramp angle to avoid subcritical operation is avoided for the most part. The basic problems of importance are the effects of airframe on the inlet, the installed inlet forces, and the effects of the inlet on the airframe which includes flow changes at downstream lifting surfaces. Operation over wide ranges of angle of attack, angle of bank and Mach number will provide many aerodynamic problems for future airbreathing missiles.

2.2 Mutual Interference Between Inlet and Airframe

Consider first the interference effect of the airframe on the inlet. Inlets are often tested alone with uniform onset flow, but when they are mounted on a body the onset flow is not uniform. The onset flow can vary in Mach number, flow direction and magnitude, and it may possess vorticity and total pressure losses. A basic problem is to locate the inlet in a region of high mass flow rate per unit area and high total pressure to keep the inlet small. Inlet placement from the viewpoint of stealth is also important but at odds with inlet performance considerations.

The effect of the inlet on the airframe is complicated and important and it depends very much on the quantity of air flowing through the inlet. Data Illustrating this effect are available from Reference 8 on the drag of the F-15 airplane with two-dimensional inlets forward of the wings. The inlets have three ramp angles. Tests were performed of the inlet installed on the airplane but mounted on a balance independent of the airplane. Airplane and inlet forces and moments were individually measured as a function of angle of attack and mass flow through the inlet. The inlet mass flow was controlled by choking the flow in a tube into which the flow exhausts at the rear of the aircraft. Figure 1 shows how the airplane drag varies with capture area ratio (mass flow ratio) at various angles of attack. The quantity A_c is the streamtube capture area for $\alpha = 0$ with the shock at the throat of the inlet. Data were not obtained to $A/A_c = 1$ because of choking in the tube. Significant increase in drag occurs in the low angle of attack range as a result of the reduced mass flow ratio.

Figure 2 shows how the inlet drag and lift coefficients vary with angle of attack and mass flow ratio for the same case as Figure 1. The reference area is now the capture area A_c. Note that reduction of capture area ratio at constant angle of attack increase the inlet lift and drag substantially. The drag of two inlets at $\alpha = 0°$ varies from 29% of the total airplane drag at $A/A_c = 0.4$ to 15% at $A/A_c = 0.7$, illustrating increase in drag due to off-design operation of the inlet. We have used this airplane case since comparable data for a missile are not available.

The variable mass flow into an inlet has an influence on the stability and control of the airframe. In subcritical operation, more flow will go around the inlet (spill) and the pressures on the fuselage and tail will be influenced. Not only is the trim of the airframe influenced by spillage, but so also is tail control effectiveness. There does not seem to be a good data base on this subject, nor do any reliable prediction methods for missiles appear to exist.

2.3 State of Prediction Methodology for Flow Fields

Let us consider the role of finite-difference methods, panel methods, and hybrid methods in treating inlet-airframe flow fields including flow at the tail. With regard to Euler codes, it is possible at this time to solve a two-dimensional or axisymmetric problem for interaction between an internal and external flow[9]. In such solutions both the internal and external flows must be covered by the mesh and the solution developed in time from some assumed initial conditions. The mass flow ratio for the inlet is controlled by the downstream boundary condition of the internal flow and is generally not directly controllable. The type of downstream boundary condition to use is not clear. An achievable back pressure may be specified with a uniform flow as an approximate boundary condition. A large number of time steps are required before the wave system stabilizes so the calculation is lengthy. The subcritical case takes longer than the supercritical case. For the supercritical case the external flow up to the normal shock can be carried out by time marching in the streamwise direction. However, for the subcritical case the three-dimensional calculation appears beyond the state of the art. Euler codes should be good for matching internal and external flows and thus getting the external aerodynamics well. However, the internal aerodynamics may be inaccurate if viscous effects are large.

The application of supersonic panel methods to predicting loads on complete configurations without inlets is an accomplished fact[10,11]. An approximate panel method accounting for flow into the inlet has been used by Dillenius[12] in a supersonic external store separation program. In this approach panels which permit variable nonzero normal velocity are placed across the streamtube entering the inlet. In this fashion the effect of mass flow ratio on the external flow is accounted for. The method appears to have the potential for accounting for subcritical flow as well as supercritical flow. It is also possible to control the mass flow ratio as a parameter in the panel method.

A third approach to flow-field analysis is to use approximate equations in the regions where they are valid and to patch the solution together in an attempt to reduce computer time. As an example, a marching code might be used up to the inlet normal shock, a Navier-Stokes code in the region of the shock, and some code such as a parabolic NS code in the diffuser.

A handbook of experimental data for the effects of inlets on airbreathing missile external aerodynamics is embodied in Reference 13.

3. Vertically Launched Missile With Transonic Turn-Over

There is a need for a vertically launched missile that can turn over horizontally at low altitude very quickly after launch. Such a need arise for defense from low-flying threats such as missiles, RPV's, helicopters, and airplanes. Also, such a missile and launcher are required to eliminate the need for trainable missile launchers that are frequently pointed in the wrong direction. Vertical launch is required because the threat may come from any direction for combat at the forward edge of the battle area.

The requirements for vertical launch are very severe. The missile must get aloft and turn over as quickly as possible. This means that it will be subject to large normal accelerations and must have a short time constant in pitch. An example of the variation with time of the predicted flight parameters is shown in Figure 3 as taken from Reference 14 for a range of nine nautical miles. Angles of attack of up to 30° are experienced with corresponding high normal accelerations. For shorter ranges, higher angles of attack will be met.

A number of interesting problems arise in connection with the design of such a missile, a partial list of which follows.

1. Over the transonic/supersonic range of high angle of attack operation how can we achieve a high turn rate; that is, powerful pitch control.

2. To what extent should aerodynamic or thrust vector control be used?

3. What type of aerodynamic control is best?

4. Will asymmetric vortices complicate the design of the control system?

If wings are used to obtain the high normal accelerations, planforms which have small shift in axial center-of-pressure location with Mach number and angle of attack such as delta wings should be used. A body-alone might be used together with thrust-vector control.

In a study of the type of control systems for a vertically launched missile, the authors of Reference 14 arrived at a combined system utilizing a body-tail configuration plus an ejectable jet-vane control. The jet-vane control is particularly useful during the low dynamic pressure part of the trajectory. The combination of controls increases the available maneuverability.

With regard to aerodynamic controls, one might consider canard controls, wing controls, or tail controls of the all-movable kind. Canard and wing controls are known to stall at lower angles of attack than tail controls since their control deflections are additive to angle of attack. Canard and wing controls however show poor roll control because of interference effects on the tail (the exceptional case occurs when the wing control fin span is much greater than the tail fin span). Control by a tail alone has the well-known disadvantage that it puts the trimming force in the opposite direction to the desired maneuver and thereby increases the missile time constant. It's hinge moments are influenced by body vortices and are nonlinear. In selecting the fin planform and airfoil section special attention should be paid to the transonic regime where control effectiveness can be very low and hinge-moments high due to transonic nonlinearities. Figure 4 from Reference 15 illustrates the effectiveness of pitch control at high angles of attack at two transonic Mach numbers. The factor k_W is basically the ratio of the normal force developed by the all-movable control panel to half of that developed by the wing alone at an angle of attack equal to $\alpha + \delta$. These data are for canard fins with an aspect ratio of 3.53, a taper ratio of 0.06, and ratio of body radius to fin semi-span of 0.4. The problem of good all-movable controls for large $\alpha + \delta$ at transonic speeds is an unsolved one. Control effectiveness and hinge moment are strongly influenced by both planform and airfoil sections. Neither a good data base nor a good predictive method exist for selecting the control.

The well-known subject of "induced yaw," the appearance of large side forces and yawing moments on a body of revolution at large angles of attack, could be a limitation on the amount of controllable normal acceleration available to a transonic missile. The onset of such asymmetric forces is determined by body fineness ratio and nose bluntness for bodies of revolution. For a fineness ratio of about 10, an angle of attack of about 25° to 30° marks the onset of asymmetry. Asymmetry starts to disappear when shock waves form on the sides of the body for crossflow Mach numbers above the critical speed which is about 0.4 for a circular cylinder. From $M_c = 0.4$ to 0.8 the magnitude of the side force as a fraction of the lift or normal forces descreases until it essentially disappears at $M_c = 0.8$. Figure 5, from an article by Wardlaw and Morrison[16], exhibits data showing this trend. If these limits for the transition of asymmetric vortices to symmetric vortex regions are adopted, and if $\alpha = 25°$ is taken as the boundary between concentrated symmetric and asymmetric vortices, then the diagram shown in Figure 6 results. By plotting the same data of Figure 5 against free-stream Mach number, Wardlaw and Morrison[16] show that the induced yaw is greatly reduced at supersonic speeds and disappears for Mach numbers greater than 1.3 except in a few instances.

There are several other ways of alleviating the asymmetric vortex switching problem besides avoiding the region $\alpha > 25°$ and $M_\infty < 1.3$. The use of vortex generators on the nose has been shown by Clark, Peoples, and Briggs[17] to eliminate induced yaw. An approach to harnessing induced yaw is fixing the asymmetry with a nose strip or proturbance and simultaneously controlling the roll attitude of the missile. If this is done, it is possible to fly at an increased maneuvering load equal to $\sqrt{C_L^2 + C_Y^2}$. In this case one would want to maximize the square root for maximum maneuverability. Innovative ideas for controlling induced yaw are still needed.

4. The Search for High L/D at High Speeds; Waveriders

4.1 Introductory Remarks

The need for ground-launched or air-launched missiles which fly out far and fast and intercept launch platforms beyond the range of their attacking missiles has lead to the studies of the hypersonic airbreathing missile. A number of feasibility studies have been made to determine aerodynamically efficient missile shapes which meet this mission. Hunt, et al.[18] have proposed a mid-inlet conept; Krieger[19] has proposed a noncircular body concept and a lifting body concept; Rasmussen[20] and Schindel[21] have adapted the waverider airplane concept to hypersonic missiles. We will briefly describe these concepts and then discuss waveriders in greater detail.

4.2 Genesis of High Speed Configurations

Current rocket-powered missiles developed in the USA employing cruciform fins mounted on bodies of revolution have been designed principally for maneuverability or other characteristics, not for high lift/drag ratio or long range. Accordingly, it is not surprising that their lift/drag ratios at Mach numbers greater than 3 are low and become lower with increasing Mach number.

The mid-inlet concept of Hunt, et al.[18] for a hypersonic missile is shown in Figure 7. This is a sketch of the proposed design of a missile to fit a U.S. Navy vertical launching system (VSL), to be boosted to $M_\infty = 4$ by a booster, and to cruise at $M_\infty = 6.0$. One of the aerodynamic considerations in the design is to make use of the high air density on the windward side of the missile to give sufficient thrust to maneuver at angle of attack. Another point is that the boundary layer is sufficiently thin on the windward meridian that boundary-layer diverters may not be required for the inlet. (The question of the shock layer still remains.) By specially tailoring the nose and forebody to make it flatter in front of the inlet, the inlet flow can be improved and its lateral divergence lessened.

The Air Force Flight Dynamics Laboratory over the past years has pursued a line of investigation to exploit the aerodynamic potential of supersonic missiles to achieve significant improvements in performance for tactical long-range air-to-air missions. The concepts which have emerged are termed "aerodynamic configured missile" (ACM). Once concept taken from Krieger[19] is a "noncircular body cruiser" as shown in Figure 8. One novel aerodynamic feature of this design is the spatula nose and flat bottom which produce high L/D ratio and neutral stability to $\alpha = 20°$. The high wing and twin vertical tails provide good lateral-directional stability characteristics. An L/D ratio of 5 to 8 at $M_\infty = 4.0$ is quoted. Because of the large range of operating conditions, a two-dimensional inlet with variable internal contraction ratio is needed to maintain high pressure recovery during cruise and climb. A two-dimensional variable geometry nozzle provides the capture area necessary for cruise and climb. In seeking the highest L/D configuration, it was found that $C_{D_{min}}$ was a controlling parameter. Since for a symmetric parabolic drag curve (C_D vs. C_L),

$$\left(\frac{L}{D}\right)_{max} = \frac{1}{2}\sqrt{\frac{C_{D_{min}}}{(C_{D_i}/C_L^2)}} \qquad (1)$$

with

$$C_{D_i} = C_D - C_{D_{min}}$$

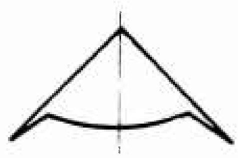
control of both minimum drag and drag-rise factor (C_{D_i}/C_L^2) is needed for maximum L/D ratio.

Another efficient aerodynamically configured missile emerging from the study is the lifting body missile shown in Figure 9. This configuration used a triangular body with wing tips and an inlet on the lower surface. It is noted that both of these missiles tend to look like airplanes. The lack of radomes in the design is noteworthy.

Another type of hypersonic missile design which is receiving current consideration is the waverider. The most elementary form of waverider is due to Nonweiler[22] and has the form shown in Figure 10. It is also termed the caret wing because of its similarity to the proofreader's mark. At the design condition the upper surface of the wing is streamwise and has no pressure drag. A planar shock stretches across the lower surface between the wing leading edges, producing a uniform pressure between them. The wing thus rides the wave and hence the term waverider. At off-design conditions the leading edges can be subsonic or supersonic.

The waverider concept has been extensively studied in Great Britain for its potential application to hypersonic aircraft. The late Dietrich Küchemann in his delightful book "The Aerodynamic Design of Aircraft"[23] has an extensive discussion of waverider technology. In this country, Rasmussen[20] and Schindel[21] have started to exploit this technology by applying it to the hypersonic missile.

A large number of waverider concepts are available. A simple way to obtain the on-design shape of a waverider is to consider, for example, a conical flow as over a circular cone or elliptical cone at angle of attack. Many streamsurfaces exist between the cone surface and the shock wave. The cross-section of a conical waverider is then formed by the body, the shock wave, and two such streamtube surfaces. This is possible since the flow above and below the streamtube surfaces cannot communicate pressure effects except possibly through the boundary layer. Examples of waveriders derived from cones by Rasmussen[20] are given in Figures 11 and 12. The wave rider shapes studied by Schindel[21] are of the following cross-sectional shape. At $M = 5.9$



Schindel gets an L/D of 4. Higher values are predicted for caret wings[23].

When a waverider with conical flow on design goes off design, either by changes in angle of attack or Mach number, the aerodynamic surface pressures show smooth variations with these variables. It is possible to derive efficient waveriders using nonconical flow at the design point. The primary problem in conical or nonconical design is to get good volume into the waverider with high L/D ratio. One interesting question concerns the general lack of axisymmetric noses or leading-edge bluntness with waveriders. Axisymmetric noses are desireable to minimize radome boresight error and bluntness is needed for aerodynamic heating reasons. It appears that such waveriders can be constructed using Euler codes coupled with blunt nose starting solutions. The penalties for bluntness need assessing.

There are a number of problems that need attention for waveriders. First, the questions of integrating the airframe with the engine needs attention. Some ideas for incorporating inlets have been advanced by Rassmussen[24]. Good ideas for incorporating controls are needed. Base drag is a problem for waveriders, and the use of boattail to lessen base drag is feasible[23].

There are a number of viscous problems concerning waveriders of which friction drag is one. All present methods of deriving waveriders shapes ignore separation, yet probably most waveriders will experience separated flow at the sharp leading edges for some Mach numbers. At high Mach numbers transition is delayed to high Reynolds number, and a large part of a waverider might encounter laminar flow. At reattachment lines the heat transfer rates can be high even if the location is on the leeward side of the missile. The art of estimating heat transfer rates is well developed and can be applied to waveriders. However, there are still problems of heat transfer as influenced by separation, reattachment, and shock-wave intersections.

One problem that has arisen with respect to waveriders is how to calculate their characteristics at off-design conditions. It appears that Euler codes can be applied fruitfully to this problem although they have not been so far.

5. High Angle of Attack Aerodynamics

5.1 Introductory Remarks

The aerodynamic problems of missiles at high angles of attack have received much attention in the last few years, but the problems are only partially solved. The importance of high angles of attack arises primarily from the need for greater maneuverability to intercept [illegible] targets or to perform evasive action. The problems are mostly associated with nonlinearities which are induced either by vorticity effects or compressibility effects or both. A recent survey of high α nonlinearities and means for calculating them is given in Reference 25. There are fundamental differences between some of the nonlinear phenomena at transonic speeds and those at supersonic speeds that are a consequence of stall and vortex behavior.

5.2 Transonic Versus Supersonic Problem Areas

One of the high α nonlinearities, which occurs at transonic speed but not at supersonic speed, is wing stall. An example of effects of wing stall on normal-force coefficient and axial center-of-pressure position are shown in Figures 13 and 14, respectively. Results are shown for two wings of Æ = 2.0 and λ = 0.5 for M_∞ = 0.8. Wing P_8 has a thickness ratio of 8.85 percent at the root chord and is a wing of uniform thickness except for 30° wedge angles normal to all edges. Wing T_{23} on the other hand has a root chord thickness ratio of 4.9 percent increasing to 9.7 percent at the tip. The sections are double wedges in the tip region and modified double wedges inboard. These data are taken from Reference 26 wherein their original sources are quoted. Note the stall of the thicker wing in Figure 13 and the larger center-of-pressure travel of the thinner wing in Figure 14. There is no stall at M_∞ = 1.2 and the curves coincide up to 20° but differ as much as 0.2 in C_N at higher angles of attack.

The point I want to make is that airfoil section effects are important on transonic wing normal force and center of pressure at high angle of attack due to stall, and this effect is absent at M_∞ = 1.2 and above. This makes a prediction method for transonic wing-body or wing-body-tail combination difficult for high angle of attack since it must account for the effects of airfoil section on stall. Present predictive methods are data-base methods[27,28] and apply strictly only to the airfoil sections used in the tests. While this difficulty is present, it is usually ignored in preliminary design. Areas where it cannot be ignored is in control effectiveness (fig. 4), hinge moments, and control cross-coupling. Predictive methodology is largely lacking in these important areas.

Returning now to the important transonic problem of induced yaw, Brian Hunt has summarized the present state of knowledge in Reference 29. It is known from vortex-cloud theory that the separation points on bodies of revolution at transonic speed can be estimated by the Stratford criterion based on adverse pressure gradients. However, for supercritical crossflow the asymmetric vortex effects are achieved or eliminated with the appearance of strong shock waves in the crossflow. What is interesting in this case is that separation occurs at nearly uniform pressure for some reason, possibly due to forward influence of the shock wave.

5.3 Some Supersonic/Hypersonic High α Problems

5.3.1 High α wing theory

While a large body of theory exists for the design of subsonic and supersonic wings at low angles of attack, there is no general method for wings at high angles of attack. This fact probably results from the complexity of the viscous phenomena including separation at high angles of attack. Examples of the various types of leeward flow over a thick delta wing are shown in Figure 15 as taken from Reference 30. In this figure the Mach number in a plane normal to the leading edge is the abscissa and the angle of attack in that plane is the ordinate. Without describing the various flows in detail, it is sufficient to say that six different cases are differentiated. Four of these cases involve leading-edge separation which can be handled by a Kutta condition. This lends some promise to the hope that the Euler equations can be used to develop a general theory of supersonic wings at high angles of attack[25]. Eventually, the Navier-Stokes equations will prevail.

5.3.2 Wing-body interference at high α

Most airplanes and missiles encounter favorable wing-body interference at low angles of attack through most of the speed range as a result of increased wing lift due to body induced upwash. However, at high angles of attack and high speeds the strong nose shocks significantly reduce the dynamic pressure at a wing position. In fact, the interference can turn from highly favorable to highly unfavorable. This result is for conventional fins mounted on a body of revolution. A number of ways of improving high M and α wing-body interference include wing blending, and unconventional configurations (waveriders). Other concepts are needed.

Fin problems at high angles of attack, in addition to adverse wing-body interference, include loss of control effectiveness, control cross-coupling, and induced rolling moments. A simple example will illustrate all three problems. Consider a cruciform wing-body at high angles of attack such that the density on the leeward side of the body is very low, approaching a vacuum. With the configuration in the + position, call for a yaw command by equally deflecting the upper and lower fins. The normal force on the upper fin is far less than that on the lower fin so that a large rolling moment is induced as a result of yaw control. If the missile rolls so that the upper fin is in the body vortex, a further rolling moment is induced. These severe nonlinearities greatly complicate the stability and control of cruciform configurations at high angle of attack. The nonlinearities can be greatly reduced by utilizing a monoplane bank-to-turn configuration. One wonders to what limits cruciform missiles can be operated before reaching their ultimate capability.

5.3.3 Wing-body-tail interference

For wing-body-tail configurations, wing-tail interference is an important cause of nonlinearities in the range up to about 20° angle of attack. Both roll angle and wing deflection contribute to the nonlinearities. These nonlinearities include loss of longitudinal stability, large induced rolling moments, and loss of fin normal force. At higher angles of attack, depending on the distance between the wing trailing edges and the empennage, the wing and forebody vortices pass well above the tail, and cause much diminished nonlinearities. However, now the afterbody section between wing and tail sheds its own vortices which impinge on the tail. These afterbody vortices are not necessarily symmetric since the missile may be rolled or the wings deflected to cause asymmetric flow over the afterbody. A powerful new series of nonlinearities thus come into play for angles much above 20°. One scheme for handling these nonlinearities does a fair job of predicting longitudinal characteristics[27] but needs improvement in calculating lateral/directional characteristics. The problem area is a difficult one which needs more attention.

5.3.4 Vorticity effects; noncircular bodies

There are a number of reasons that missiles will use noncircular bodies to a greater degree in the future. Airbreathing missiles will have noncircular bodies because of inlets and ducts; bank-to-turn missiles do not require round bodies. Also, the use of square bodies to enhance internal packaging and submunition deployment is under active development[31]. They may also be of importance becuase of radar crosssection. It is not possible to predict the high angle-of-attack aerodynamics of these noncircular bodies in supercritical crossflow using any theory but that of Navier-Stokes because of flow separation. For subcritical crossflow, where separation is still controlled by adverse pressure gradients, it is possible to apply vortex-cloud theory with some success. An example of such a calculation is shown in Figure 16 following Mendenhall[32].

5.3.5 Status of engineering prediction methods

A number of engineering prediction methods exist for defining the forces and moments acting on wing-body and wing-body-tail combinations from subsonic to hypersonic speeds. Ten of these methods are reviewed by Williams in Reference 33. All apply to cruciform configurations, about half to lifting bodies, and several to airbreathers. While most have angle of attack capabilities to α = 40°, the accuracies of the methods are not good to such high angles, particularly for lateral/directional characteristics which about half do not treat. Most do not have all-movable control capability, and none handles control characteristics accurately through the entire range of applicability. There is a need for better design tools for high angles of attack, both for conventional cruciform missiles and other advanced configurations, including lifting body types and airbreathers. Reliable prediction methods for lateral/directional stability and control parameters for angles or attack greather than 20° remain to be accomplished.

6. Some Observations on the Application of CFD To Missile Aerodynamics

6.1 Methods Other Than Navier-Stokes

In Reference 34, Klopfer and Nielsen survey the application of CFD to missile aerodynamics. Some of the applications noted in that paper are listed in Figure 17(a) for methods other than the Navier-Stokes methods and in Figure 17(b) for the Navier-Stokes methods. References 35-59 are covered in the figure. Figure 17(a) shows that the inviscid methods of transonic small disturbance theory and of full potential theory have been applied by several investigators to bodies and fins with no flow separation. In addition, three cases of application of the Euler equations are considered. The first case is that of the straight Euler equations with no boundary layer and the second case is with boundary layer displacement thickness included. The third case is the case of the Euler equations in which the separation lines are specified as input data and a Kutta-like condition is introduced at the separation lines. This latter approach yields good results for those cases where convection of vorticity overshadows any effects of diffusion of vorticity.

A few words on the Kutta condition are in order. It was found in Reference 44 that at the sharp subsonic leading edges of missile fins five boundary conditions can be specified without over-determining the problem, and the choice of these conditions involves some arbitrariness. Some of these arbitrary boundary conditions have only a small effect which is confined locally to the neighborhood of the edge. The dominant boundary condition that determines the vorticity shedding rate at the edge is the requirement that the flow leaves the edge in a plane tangent to the extended chord plane, a Kutta-like condition. A set of boundary conditions can also be specified for a separation line on a body of revolution which properly predicted the vortex shedding rate from the body as shown in Figure 18. Fair agreement between the flow field as predicted and as measured was obtained except near the top of the body where secondary separation was ignored.

This experience appears to be contradictory to that of Schmidt, Jameson, and Whitfield[52] who found that they did not have to impose a Kutta condition when applying the Euler equation to an airfoil with a sharp trailing edge. Also, Eriksson and Rizzi[60] has a similar experience when applying the Euler equations to airfoils and a delta wing with sharp subsonic leading edges.

A simple explanation can resolve these differences. We must differentiate between distinguished separation locations like sharp trailing edges the location of which are known a priori and other separation locations like the separation line on a body of revolution which are not known a priori and which are Reynolds number, Mach number, and angle of attack dependent. It is known that the action of viscosity is to make a sharp trailing edge a separation location. However the potential equations cannot handle the trailing vortex sheet explicitly because it is rotational. The Euler equation, which can support a rotational flow, might be expected to recognize a Kutta condition if viscous effects could be introduced into them. It is probable that the artificial viscosity introduced by the algorithm provides the necessary mechanism for the Euler equations to do this, and separation will appear at the distinguished location since its position is not Reynolds-number dependent.

The Euler equations are also known to produce separation on cones and other bodies of revolution[44]. However, the separation does not appear at the correct position since the effective Reynolds number due to artificial viscosity is usually incorrect and it is also grid-dependent. Accordingly it is necessary to introduce a separation line based on experiment and Kutta-like boundary conditions to get good results for separated flow on bodies which do not have distinguished separation locations.

6.2 Navier-Stokes Methods

In figure 18(b) three different versions of the Navier-Stokes equations are listed for both laminar and turbulent flow. The thin-layer Navier-Stokes equations are obtained by neglecting viscous terms in the streamwise and/or spanwise direction. This is justified on the grounds that gradients in the boundary layer normal to the wall are much greater than in the other directions. No wing-body combinations have been attempted using these to the best of our knowledge.

The parabolized Navier-Stokes equations are a simplification of the full Reynolds-averaged Navier-Stokes equation by neglecting the unsteady terms and by modifying the streamwise convective flux vector. This makes the equations hyperbolic/parabolic in the streamwise direction. For steady supersonic flow, this permits marching in the streamwise direction. It is possible to get solutions for many cases of interest within present computer resources. The method is stable if the subsonic part of the flow (boundary layer) is small. Large-scale separation generally cannot be handled by the PNS equations, not only because of stability, but because of the lack of a good turbulence model.

The full Navier-Stokes equations are applicable to missiles at any speed or angle of attack. However, their general application is limited by computer resources and turbulence modeling. The only application to a wing-body combination was made by Shang[54], for zero angle of attack, but no angle-of-attack cases seem to have been run to date.

6.3 Future Directions

It is of interest to speculate on the application of CFD to complete missile configurations in the future. It is probable that panel methods and Euler equations will be the principal tools for complete configurations for some time to come. The Euler equations are just emerging in this connection, and a great deal of work is needed in all areas from mesh generation to finding better ways of treating separation. The limits of applicability and the accuracy of the Euler equations in various cases need to be determined. It will be a long time before Navier-Stokes equations will be used routinely in conceptual design. While the size of existing computers is a limiting factor, it may not be so limiting as the lack of understanding of turbulent modeling for separated compressible flow.

Some specific advancements which could aid future applications of CFD aerodynamics include both calculative and experimental efforts. These include:

1. Special data to help formulate the Euler equation boundary conditions for separated flow near sharp edges.

2. Experimental separation-line data on noncircular bodies.

3. Starting solutions for the Euler equations for spatula noses.

4. Starting solutions for blunt nonspherical noses with detached shocks.

5. Prediction of vortex bursting at high Mach numbers.

6. Method of predicting vortex formation in wing-body junctures.

7. Other Areas Impacting Future Missile Design

A number of other areas influencing future missile design will be mentioned but will not be discussed in any detail for lack of time. The areas are supersonic carriage and separation of stores, aerothermal design, and radar cross-section.

It is well-known that an airplane with a load of external stores mounted on pylons has too much drag to fly at supersonic speed. This has led to a multitude of concepts for other methods of carrying and launching "external" stores, including the following ones:

1. Conformal
2. Semi-submerged
3. Cavities and open bays
4. Internal carriage
5. Topside carriage
6. In pod with salvo launch

Work needs to be done to determine which of these concepts or other ones are the most promising, and then research needs to be concentrated on the promising ones. The impact on missile design comes about from constraints for carrying the stores and for providing safe launch.

With regard to aerothermal design, the general problem areas are well known for ICBM and space shuttle technology. Also the methods for predicting heat transfer are fairly well developed. Special problems exist for missiles with regard to fin-body junctures on windward sides, and with hot spots near separation and reattachment regions and in the neighborhood of shock impingement. In addition, IR seekers are limited by self noise as well as thermal shock of their brittle ceramic materials. When boundary layer transition occurs on the seeker dome, the resulting increase in heating at the dome base leads to hoop stresses that may cause failure of the material. There are similar thermal problems with radomes and leading edges which may require large radii at the expense of drag.

Since the total temperature at Mach 6, 100,000 ft. altitude is about 3400° R, airbreathing engine and air inlet components must be fabricated from refractory metals and insulated with nonablative materials such as Zirconia. In such design, thermal control via radiation losses becomes an important factor.

In applications where radar cross-section must be minimized, there could be a definite impact both on the design of the missile and on its carriage position on the aircraft. Providing minimum radar cross-section with high aerodynamic efficiency will be a definite problem in certain applications. In RCS minimization, the emphasis is upon bodies with multiple differing diffraction paths, leading to noncircular cross-sections, rounded bases, and non-cruciform fins to avoid corner reflectors.

8. Concluding Remarks

A number of trends in future missile design have been discussed with respect to the ways in which they influence aerodynamic design. Among the subjects discussed are:

a. Airframe-inlet interference in airbreathing missiles.

b. Transonic aerodynamic problems for vertically launched missiles with quick turn-over.

c. Obtaining high L/D at hypersonic speeds.

d. Waveriders; aerodynamically configured missiles.

e. High angle-of-attack problems.

f. Status of CFD applied to missile aerodynamics.

g. Supersonic carriage and launch of stores.

h. Aerothermal design.

i. Radar cross-section.

A number of specific suggestions have been made where more work is required in the above areas including the following ones.

1. Methods for determining the effects of airframe-inlet interference on drag and stability and control are inadequate. Panel methods may be helpful in this area.

2. For missiles which must operate at high angles of attack in the transonic range, special nonlinearities need attention. These include better control systems and control prediction methodology, elimination or harnessing of induced yaw, and higher normal accelerations.

3. Better aerodynamic efficiency at hypersonic speeds (high L/D) is needed.

4. While waveriders are promising in connection with 3, much more work is needed to provide radomes and inlets for waveriders. Also methods for predicting their aerodynamic characteristics at off-design are generally lacking.

5. Methods for predicting control effectiveness, hinge moments, and control cross-coupling for large angles of attack and control deflection are needed for all-movable controls and other control types.

6. Ideas for producing favorable hypersonic wing-body interference with high lift-drag ratio configurations are needed.

7. Methods for predicting vortex behavior for noncircular bodies are needed for supercritical crossflow.

8. Missile engineering prediction method for lateral/directional characteristics for $\alpha > 20°$ need improvement.

9. The application of the Euler equations to complete missile configurations needs to be extended especially with respect to flow separation phenomena.

10. CFD application to missile aerodynamics needs more attention.

11. Supersonic carriage and launch, radar cross-section, and aerothermal design need increased emphasis.

REFERENCES

1. Knoche, G. H.: Trends in Missile Development and Their Corresponding Requirements with Respect to Aerodynamics. Invited Paper presented at AGARD Fluid Dynamics Panel Symposium on "Missile Aerodynamics," Trondheim, Norway, Sep. 1982.

2. McGehee, R. M.: Bank-to-Turn (BTT) Technology. AIAA Paper 79-1752, Aug. 1979.

3. Froning, H. D., Jr.: Aerodynamic Design of Slender Missiles for Bank-to-Turn Flight at High Angles of Attack. AIAA Paper 81-0289, Jan. 1981.

4. Sawyer, W. C. and Jackson, C. M., Jr.: An Overview of NASA's Role in Maneuvering Missile Aerodynamic Technology. Invited Paper, AIAA Paper 82-0247, Jan. 1982.

5. Carlson, D. R.: The Changing Role of the Aerodynamicist in Tactical Missile Design. AIAA Paper 82-0315, Jan. 1982.

6. Cronvich, L. L. and Liepman, H. P.: Advanced Missile Technology — A Review of Technology Improvement Areas for Cruise Missiles. NASA CR 3187, Oct. 1979.

7. Nielsen, J. N.: Missile Aerodynamics — Past, Present, Future. AIAA Paper 79-1819, Aug. 1979 (also J. Spacecraft and Rockets, Vol. 17, No. 3, May/Jun. 1980, pp. 165-176).

8. Kamman, J. H. and Wallace, H. W.: Assessment of Installed Inlet Forces and Inlet/Airframe Interactions. AFFDL Rept. No. AFFDL-TR-76-62, Jul. 1976.

9. Biringen, S. H. and McMillan, O. J.: An Implicit Method for the Calculation of Inlet Flow Fields. NASA CR 3413, Jun. 1981.

10. Rubbert, P. E. and Saaris, G. R.: Review and Evaluation of a Three-Dimensional Lifting Potential Flow Analysis Method for Arbitrary Configurations. AIAA Paper 72-188, Jan. 1972.

11. Dillenius, M. F. E. and Nielsen, J. N.: Computer Programs for Calculating Pressure Distributions Including Vortex Effects on Supersonic Monoplane or Cruciform Wing-Body-Tail Combinations with Round or Elliptical Bodies. NASA CR 3122, Apr. 1979.

12. Goodwin, F. K., Dillenius, M. F. E., and Mullen, J.: Prediction of Supersonic Store Separation Characteristics Including Fuselage and Stores of Noncircular Cross Section. Vol. I — Theoretical Methods and Comparisons With Experiment. AFWAL-TR-80-3032, Vol. I, Nov. 1980.

13. Perkins, S. C., Jr. and McMillan, O. J.: A Handbook of Experimental Data for the Effects of Inlets on Airbreathing Missile External Aerodynamics (U). NWC TP 6147, Jul. 1981. Vol. I — Overview and Summary (U) (CONFIDENTIAL). Vol. II — Configuration Data: Inlet Type Effects (U) (UNCLASSIFIED). Vol. III — Data Classified by Inlet Type: Part 1 (U) (CONFIDENTIAL). Vol. III — Data Classified by Inlet Type: Part 2 (U) (CONFIDENTIAL).

14. Giragosian, P.: Aerodynamic Considerations in the Design of a Vertically Launched Advance Interdiction Missile. AIAA Paper 82-1340, Aug. 1982.

15. Smith, C. A. and Nielsen, J. N.: Nonlinear Aerodynamics of All-Movable Controls. Paper 25, AGARD CP 262, Aerodynamic Characteristics of Controls, Sep. 1979.

16. Wardlaw, A. B., Jr. and Morrison, A. M.: Induced Side Forces at High Angles of Attack. J. Spacecraft and Rockets, Vol. 13, No. 10, Oct. 1976, pp. 589-593.

17. Clark, W. H., Peoples, J. R., and Briggs, M. M.: Occurrence and Inhibition of Large Yawing Moments During High Incidence Flight of Slender Missile Configurations. AIAA Paper 72-968, Sep. 1972.

18. Hunt, J. L., Johnston, P. J., Cubbage, J. M., Dillon, J. L., Richie, C. B., and Marcum, D. C., Jr.: Hypersonic Airbreathing Missile Concepts Under Study at Langley. AIAA Paper 82-0316, Jan. 1982.

19. Krieger, R. J.: Summary of Design and Performance Characteristics of Aerodynamic Configured Missiles. AIAA Paper 81-0286, Jan. 1981.

20. Rasmussen, M. L.: Waverider Configurations Derived from Inclined Circular and Elliptic Cones. J. Spacecraft and Rockets, Vol. 17, No. 6, Nov./Dec. 1980, pp. 537-545.

21. Schindel, L. H.: Design of High Performance Hypersonic Missiles. AIAA Paper 82-0391, Jan. 1982.

22. Nonweiler, T. R. F.: Delta Wing Shapes Amenable to Exact Shock Wave Theory. J. Roy, Aero. Soc., Vol. 67, No. 39, 1963.

23. Küchemann, D.: The Aerodynamic Design of Aircraft. Pergamon Press, 1978.

24. Rasmussen, M. L., Daniel, D. C., and Jischke, M. C.: Supersonic Aerodynamics of a Class of Cone-Derived Waveriders. Proc. of the Twelfth Navy Symposium on Aeroballistics, Vol. 1, May 1981.

25. Nielsen, J. N.: Nonlinear Flow Phenomena at High Angles of Attack and Recent Advances in Their Prediction. Invited Paper presented at AGARD Fluid Dynamics Panel Symposium on "Missile Aerodynamics," Trondheim, Norway, AGARD Conf. Preprint No. 336, 20-22 Sep. 1982.

26. Nielsen, J. N. and Goodwin, F. K.: Preliminary Method for Estimating Hinge Moments of All-Movable Controls. Nielsen Engineering & Research, Inc. TR 268, Mar. 1982.

27. Nielsen, J. N., Hemsch, M. J., and Smith, C. A.: A Preliminary Method for Calculating the Aerodynamic Characteristics of Cruciform Missile to High Angles of Attack Including Effects of Roll Angle and Control Deflection. Report ONR-CR215-226-4F, Nov. 1977.

28. Baker, W. B., Jr.: An Aerodynamic Coefficient Prediction Technique for Slender Bodies with Low Aspect Ratio Fins at Mach Numbers from 0.6 to 3.0 and Angles of Attack from 0 to 180 Degrees. AEDC TR-77-97, Mar. 1978.

29. Hunt, B. L.: Asymmetric Vortex Forces and Wakes of Slender Bodies. Invited Paper, AIAA Paper 82-1336, Aug. 1982.

30. Szodroch, J. C. and Ganzer, U.: On the Leeside Flow Over Delta Wings at High Angle of Attack. AGARD CP No. 247, Paper 21, Fluid Dynamics Panel Symposium, Sandefjord, Norway Oct. 1978.

31. Daniel, D. C., Yechout, T. R., and Zollars, G. J.: Experimental Aerodynamic Characteristics of Missiles With Square Cross Sections. J. of Spacecraft and Rockets, Vol. 19, Mar./Apr. 1982, pp. 167-172.

32. Mendenhall, M. R. and Allen, J. M.: Prediction of Vortex Shedding From Noncircular Bodies at High Angles of Attack in Supersonic Flow. Paper presented at AGARD Fluid Dynamics Panel Symposium on "Missile Aerodynamics," Trondheim, Norway, 20-22 Sep. 1982, AGARD Conf. Preprint No. 336.

33. William, J. E., Jr.: Evaluation of Supersonic Missile Aerodynamic Prediction Technique. AIAA Paper 82-0390, Jan. 1982.

34. Klopfer, G. H. and Nielsen, J. N.: Computational Fluid Dynamic Applications to Missile Aerodynamics. Paper presented at AGARD Fluid Dynamics Panel Symposium on "Missile Aerodynamics," Trondheim, Norway, Conf. Preprint No. 336, 20-22 Sep. 1982.

35. Bailey, F. R. and Ballhaus, W. F.: Relaxation Methods for Transonic Flow About Wing-Cylinder Combinations and Lifting Swept Wings. Lecture Notes in Physics, Vol. 19, Springer-Verlag, 1972, pp. 2-9.

36. Caughey, D. A. and Jameson, A.: Numerical Calculations of Transonic Potential Flow About Wing-Body Combinations. AIAA J., Vol. 17, No. 2, Feb. 1979, pp. 175-214.

37. Caughey, D. A. and Jameson, A.: Progress in Finite-Volume Calculations for Wing-Fuselage Combinations. AIAA J., Vol. 18, No. 11, Nov. 1980, pp. 1281-1288.

38. Deiwert, G. S.: Numerical Simulation of Three-Dimensional Boattail Afterbody Flowfields. AIAA J., Vol. 19, No. 5, May 1981, pp. 582-588.

39. Graham, J. E., Hankey, W. L., and Shang, J. S.: Navier-Stokes Solution of a Slender Body of Revolution at Large Incidence. AIAA Paper 80-0190, Jan. 1981.

40. Hankey, W. L. and Shang, J. S.: Analysis of Self-Excited Oscillations in Fluid Flows. AIAA Paper 80-1346, Jul. 1980.

41. Hung, C. M.: Numerical Solution of Supersonic Laminar Flow Over an Inclined Body of Revolution. AIAA J., Vol. 18, No. 8, Aug. 1980, pp. 921-928.

42. Hung, C. M. and Chaussee, D. S.: Computation of Supersonic Turbulent Flows Over an Inclined Ogive-Cylinder-Flare. AIAA J., Vol. 19, No. 9, Sep. 1981, pp. 1139-1144.

43. Klopfer, G. H. and Nielsen, J. N.: Euler Solutions for Wing and Wing-Body Combinations at Supersonic Speeds with Leading-Edge Separation. AIAA Paper 80-0126, Jan. 1980.

44. Klopfer, G. H. and Nielsen, J. N.: Euler Solutions of the Body Vortices of Tangent Ogive Cylinders at High Angles of Attack and Supersonic Speeds. AIAA Paper 81-0361, Jan. 1981.

45. Lin, T. C. and Rubin, S. G.: A Numerical Model for Supersonic Viscous Flow Over a Slender Reentry Vehicle. AIAA Paper 79-0205, Jan. 1979.

46. Marconi, F. and Koch, F.: An Improved Supersonic Three-Dimensional, External, Inviscid Flow Field Code. NASA CR 3108, 1979.

47. Minailos, A. N.: Calculation of Supersonic Flow Past Wings with Consideration of Tangential Discontinuities Shed from the Edges Within the Scope of a Model Using a System of Euler Equations. Fluid Dynamics, Vol. 13, No. 1, Sep. 1978, pp. 57-66.

48. Pulliam, T. H. and Lomax, H.: Simulation of Three-Dimensional Compressible Viscous Flow on the Illiac IV Computer. AIAA Paper 79-0206, Jan. 1979.

49. Pulliam, T. H. and Steger, J. L.: On Implicit Finite Difference Simulations of Three Dimensional Flow. AIAA Paper 78-10, Jan. 1978.

50. Rakich, J. V., Vigneron, Y. C., and Agarwal, R.: Computation of Supersonic Viscous Flows Over Ogive-Cylinders at Angle of Attack. AIAA Paper 79-0131, Jan. 1979.

51. Schiff, L. B. and Sturek, W. B.: Numerical Simulation of Steady Supersonic Flow Over an Ogive-Cylinder-Boattail Body. AIAA Paper 80-0066, Jan. 1980.

52. Schmidt, W., Jameson, A., and Whitfield, D.: Finite Volume Solution for the Euler Equations for Transonic Flow Over Airfoils and Wings Including Viscous Effects. AIAA Paper 81-1265, Jun. 1981.

53. Shang, J. S.: Numerical Simulation of Wing-Fuselage Interference. AIAA Paper 81-0048, Jan. 1981.

54. Shang, J. Smith, R., and Hankey, W.: Flow Oscillations of Spike-Tipped Bodies. AIAA J., Vol. 20, No. 1, Jan. 1982, pp. 25-26.

55. Siclari, M. J.: Investigation of Cross Flow Shocks on Delta Wings in Supersonic Flow. AIAA Paper 79-0345, Jan. 1979.

56. Sturek, W. B., Mylin, D. C., and Bush, C. C.: Computational Parametric Study of the Aerodynamics of Spinning Slender Bodies at Supersonic Speeds. AIAA J., Vol. 19, No. 8, Aug. 1981, pp. 1023-1024.

57. Tannehill, J. C., Venkatapathy, E., and Rakich, J. V.: Numerical Solution of Supersonic Viscous Flow Over Blunt Delta Wings. AIAA Paper 81-0049, Jan. 1981.

58. Wardlaw, A. B., Jr., Baltakis, J. P., Solomon, J. M., and Hackerman, L. B.: An Inviscid Computations Method for Tactical Missile Configurations. NSWC TR 81-457, 1981.

59. Wardlaw, A. B., Jr., Solomon, J. M., and Baltakis, F. P.: Supersonic Inviscid Flowfield Computations of Missile Type Bodies. AIAA J., Vol. 19, No. 7, Jul. 1981, pp. 899-906.

60. Eriksson, L. and Rizzi, A.: Computations of Vortex Flow Around Wings Using the Euler Equations. Proc. of the 15th CAMM Conf. on Numerical Methods in Fluid Mech., Paris, Oct. 1981.

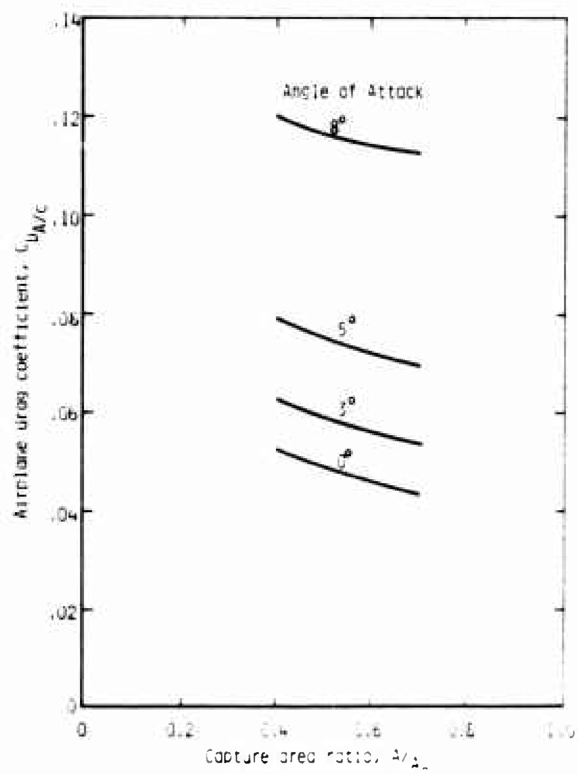


FIGURE 1.- EFFECT ON AIRPLANE DRAG COEFFICIENT OF MASS FLOW THROUGH INLET AND ANGLE OF ATTACK.

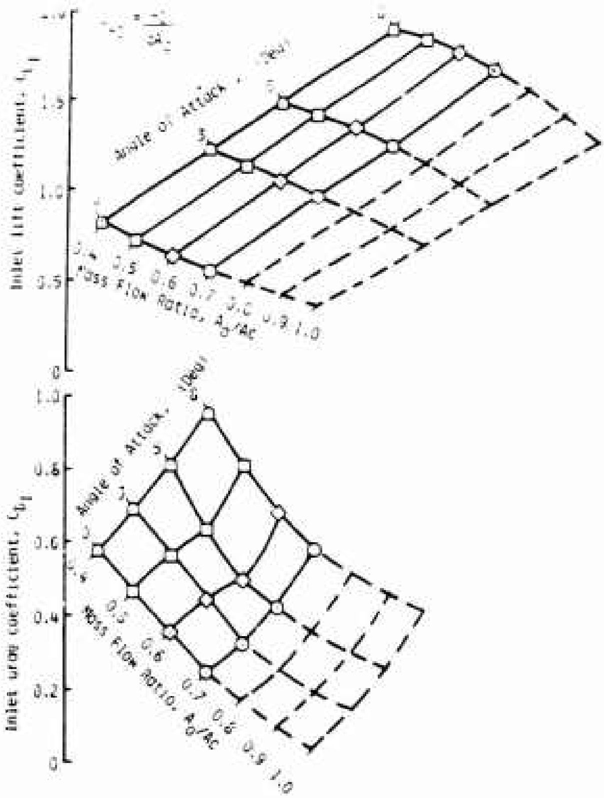


FIGURE 2.- INLET LIFT AND DRAG COEFFICIENTS AS AFFECTED BY ANGLE OF ATTACK AND MASS FLOW RATIO (A_0/A_C), F-15 INLET AT M = 1.5, ON-DESIGN, ZERO COWL DROOP.

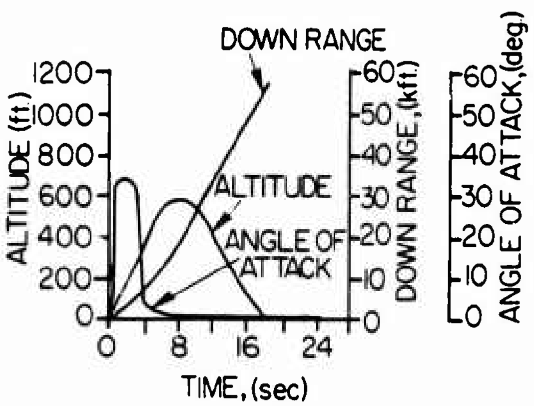
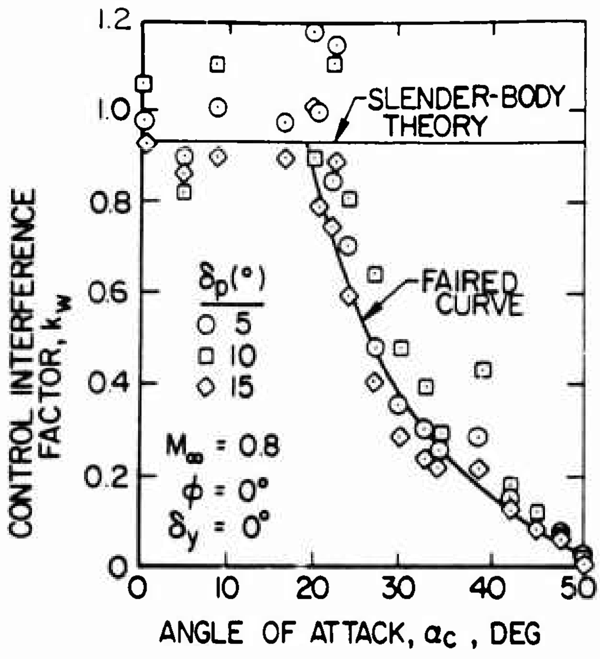
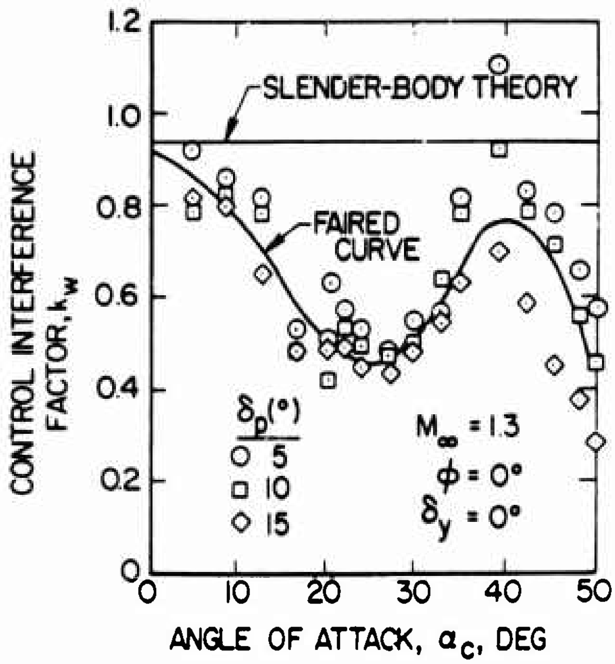


FIGURE 3.- TRAJECTORY QUANTITIES FOR A VERTICALLY LAUNCHED MISSILE WITH A RANGE OF 9 n.m.



(a) $M_\infty = 0.8$

FIGURE 4.- EFFECT OF ANGLES OF ATTACK AND CONTROL DEFLECTION ON PITCH-CONTROL EFFECTIVENESS.



(b) $M_\infty = 1.3$

FIGURE 4.- CONCLUDED.

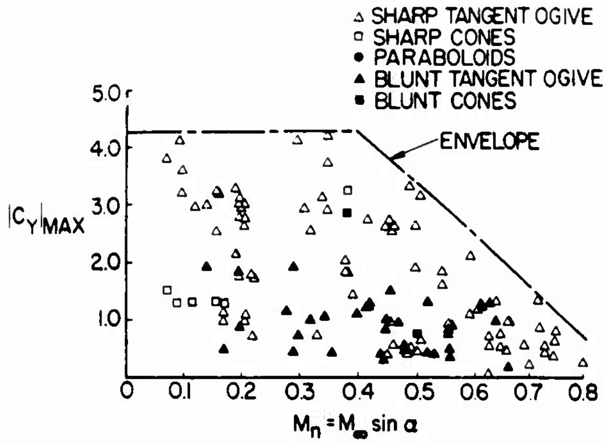


FIGURE 5.- EFFECT OF CROSSFLOW MACH NUMBER ON VORTEX-INDUCED SIDE FORCE.

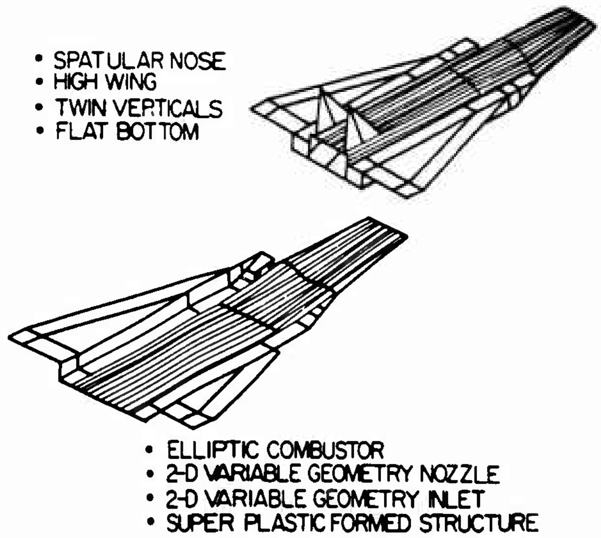


FIGURE 8.- NONCIRCULAR BODY CRUISER USING ADVANCED TECHNOLOGIES.

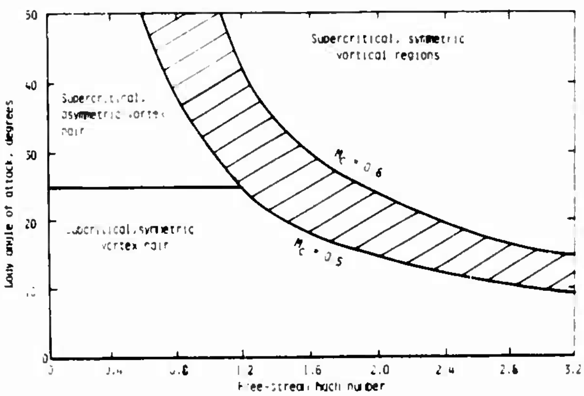


FIGURE 6.- APPROXIMATE REGIONS FOR VARIOUS TYPES OF BODY VORTICES.

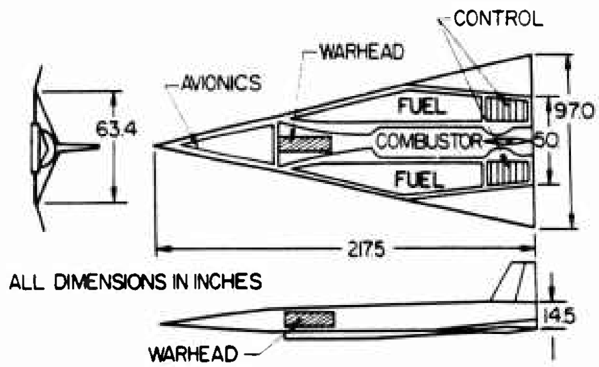


FIGURE 9.- LIFTING BODY MISSILE.

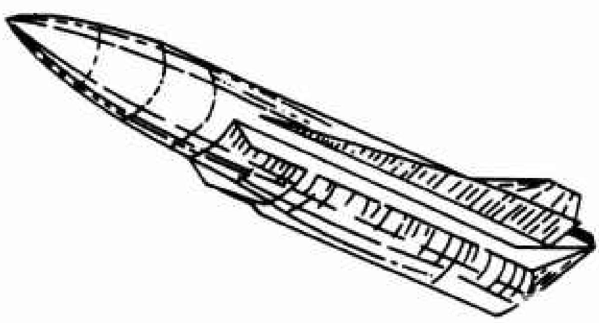


FIGURE 7.- MID-INLET CONCEPT.

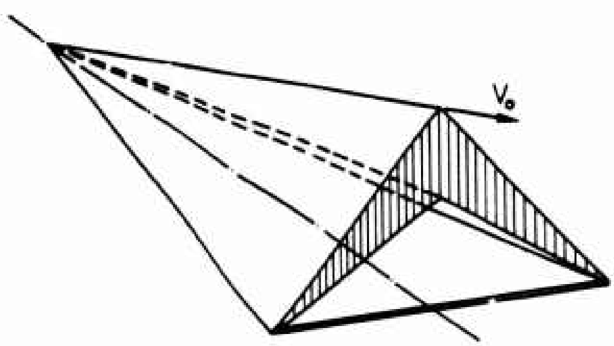
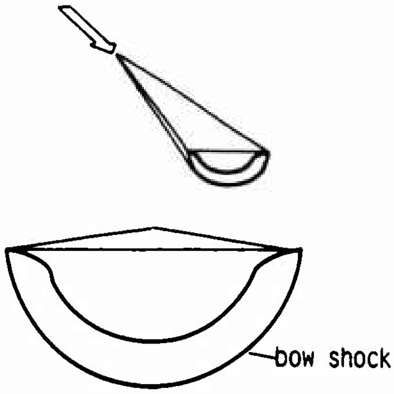
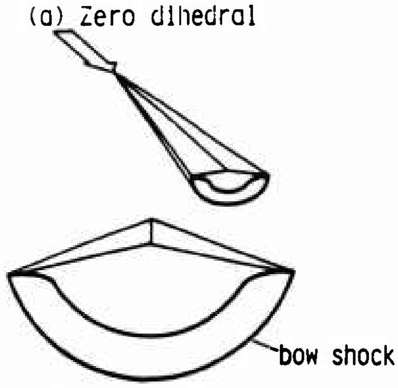


FIGURE 10.- CARET WING SUPPORTING AND CONTAINING A PLANE SHOCKWAVE. AFTER NONWEILER (1963).

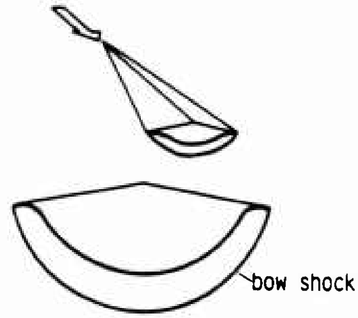


(a) Zero dihedral

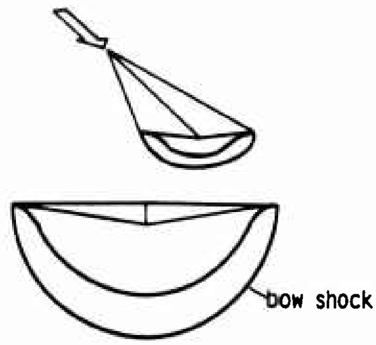


(b) Negative dihedral

FIGURE 11.- INCLINED CIRCULAR-CONE WAVE-RIDERS WITH FREESTREAM UPPER SURFACES.



(a) Positive dihedral



(b) Negative dihedral

FIGURE 12.- INCLINED ELLIPTICAL-CONE WAVERIDERS WITH FREESTREAM UPPER FACE.

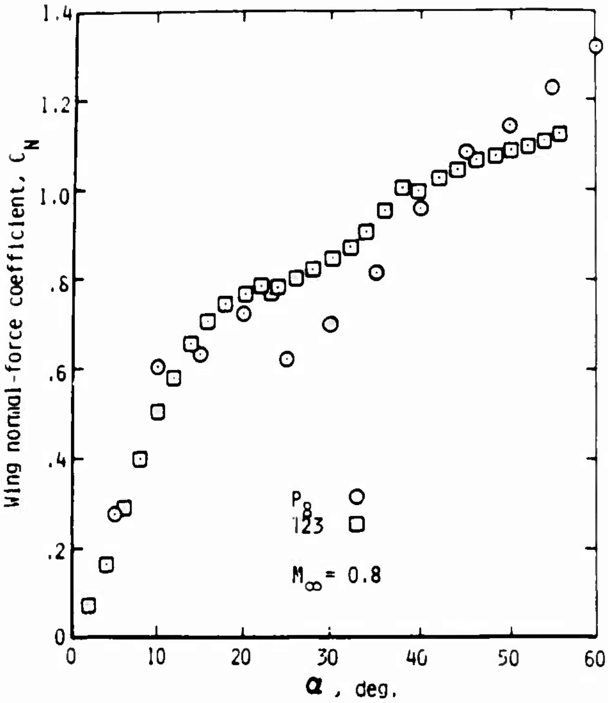


FIGURE 13.- EXPERIMENTAL NORMAL-FORCE CURVES FOR TWO WINGS OF ASPECT RATIO 2 AND TAPER RATIO 0.5 DIFFERING IN AIRFOIL SECTIONS.

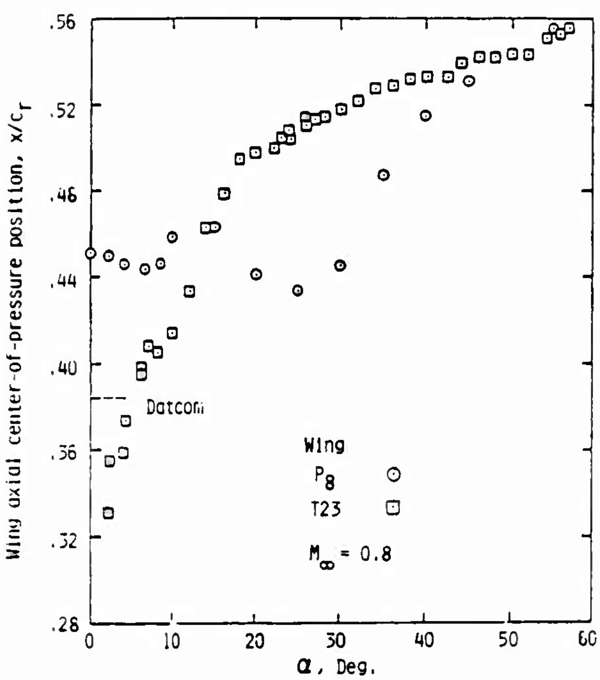


FIGURE 14.- EXPERIMENTAL CENTER-OF-PRESSURE POSITIONS FOR TWO WINGS OF ASPECT RATIO 2 AND TAPER RATIO 0.5 DIFFERING IN AIRFOIL SECTIONS.

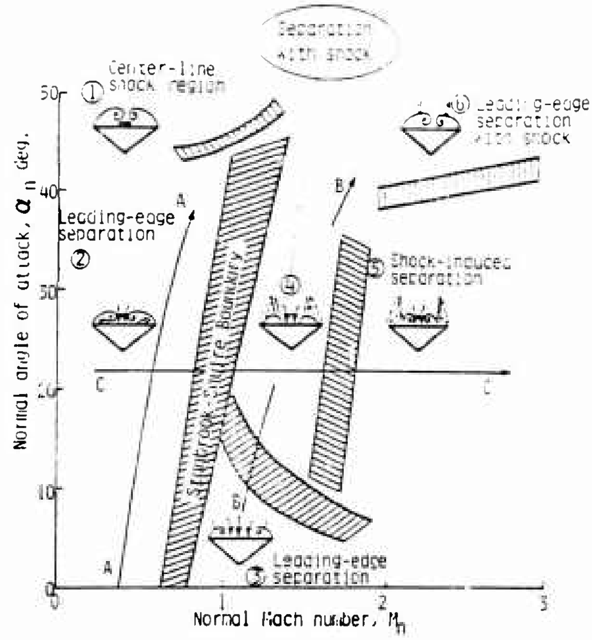


FIGURE 15. - LEE SIDE FLOW REGIMES OVER THICK DELTA WINGS AT SUPERSONIC SPEEDS. (SZODRUCH, 1978).

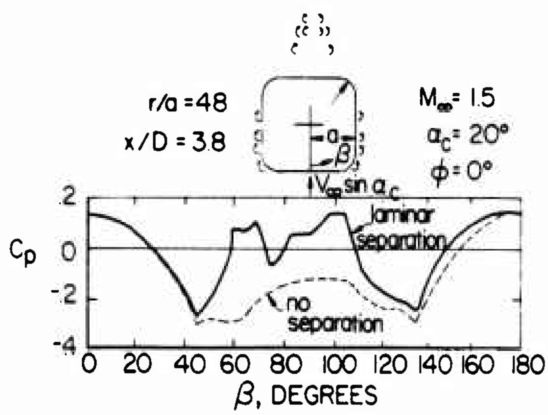


FIGURE 16.- PREDICTED PRESSURE DISTRIBUTION AND VORTEX WAKE ON A SQUARE CROSS SECTION BODY, M = 1.5, C = 20 .

Flow Configuration / Equations	Bodies With Flow Separation	Bodies & Fins No Flow Separation	Bodies & Fins Flow Separation	Unsteady Flows
Transonic Small Disturbance (TSD)		Bailey (35)		
Full Potential		Caughey (37) Caughey (36)		
TSD & BOUNDARY Layer Correction				
Euler		Siclari (55) Marconi (46) Wardlow (59)		
Euler & Boundary Layer	Schmidt (52)		Schmidt (52)	
Euler & Kutta Condition	Minailos (47) Klopfer (44)		Klopfer (43)	

(a) Non Navier-Stokes Codes

Flow Configuration / Equations	Bodies With Flow Separation	Bodies & Fins No Flow Separation	Bodies & Fins Flow Separation	Unsteady Flows
Thin Layer Navier-Stokes, Laminar	Pulliam (49) Hung (41)			
Thin Layer Navier-Stokes, Turbulent	Pulliam (48) Schiff (51) Deiwert (38) Hung (42)			
Parabolized Navier-Stokes, Laminar	Rakich (50) Tannehill (57) Lin (45)			
Parabolized Navier-Stokes, Turbulent	Rakich (50) Sturek (56) Schiff (51)			
Full Navier-Stokes, Laminar	Graham (39)			
Full Navier-Stokes, Turbulent	Graham (39)	Shang (53)		Shang (53) Hankey (40)

(b) Navier-Stokes Codes

Figure 17.- SURVEY OF CFD IN MISSILE AERODYNAMICS.

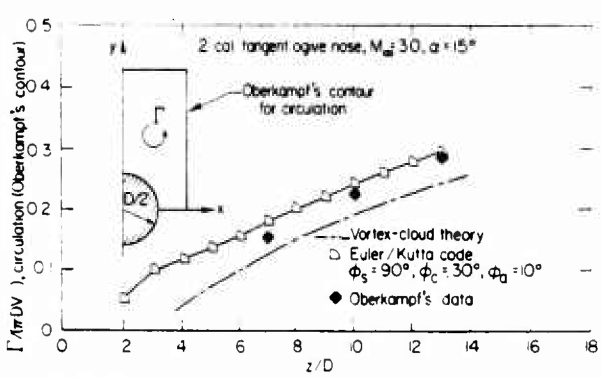


FIGURE 18.- COMPARISON OF CIRCULATION FOR EULER/KUTTA CODE, VORTEX CLOUD THEORY, AND EXPERIMENTAL DATA.